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CONSTITUTIVE PROPERTY TESTS ON TUFF TO DETERMINE RATE EFFECTS

John Q. Ehrogott

Army Engineer Waterways Experiment Station
Vicksburg, Mississippi

June 1973

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CONSTITUTIVE PROPERTY TESTS ON TUFF TO DETERMINE RATE EFFECTS

by

J. Q. Ehrgott

June 1973

Sponsored by Defense Nuclear Agency
Subtask SB209, Work Unit 10, "Laboratory Evaluation of Gage Placement in Field Grout Mixtures"

Conducted by U. S. Army Engineer Waterways Experiment Station
Soils and Pavements Laboratory
Vicksburg, Mississippi

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13. ABSTRACT

This report documents the results of a limited number of static and dynamic tests on one tuff from the location of the Diamond Mine Event tunnel at the Nevada Test Site. The tests comprised the first experimental study conducted in the then newly developed dynamic high-pressure triaxial test device. The purpose of the study was to determine loading rate effects on the uniaxial strain, hydrostatic compression, and triaxial shear response of that tuff when loaded statically (approximately 2 minutes to peak stress) and dynamically (approximately 20 msec to peak stress). The results indicated that rate effects were of secondary importance when compared with the effects of variation of water content of specimens. Primary consideration should be given to testing the tuff at its in situ water content.

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ABSTRACT

This report documents the results of a limited number of static and dynamic tests on one tuff from the location of the Diamond Mine Event tunnel at the Nevada Test Site. The tests comprised the first experimental study conducted in the then newly developed dynamic high-pressure triaxial test device. The purpose of the study was to determine loading rate effects on the uniaxial strain, hydrostatic compression, and triaxial shear response of that tuff when loaded statically (approximately 2 minutes to peak stress) and dynamically (approximately 20 msec to peak stress). The results indicated that rate effects were of secondary importance when compared with the effects of variation of water content of specimens. Primary consideration should be given to testing the tuff at its in situ water content.

PREFACE

This study was conducted by personnel of the U. S. Army Engineer Waterways Experiment Station (WES) through sponsorship of the Defense Nuclear Agency (DNA) (formerly the Defense Atomic Support Agency) under Subtask SB209, Work Unit 10, "Laboratory Evaluation of Gage Placement in Field Grout Mixtures." The investigation was conducted in support of the Diamond Mine Event, an underground test conducted at the Nevada Test Site. The study was performed during the period December 1970 to June 1971. The results in the form of a working draft were transmitted to LTC Walter V. Davis, DNA Test Command, Test Group Director of Diamond Mine in June 1971.

The study was conducted by personnel of the Soils and Pavements Laboratory (S&PL), WES. The project engineer was Mr. J. Q. Ehrgott, Soil Dynamics Division, S&PL, who also prepared the report, under the supervision of Dr. J. G. Jackson, Jr., Chief, Soil Dynamics Division. Mr. J. P. Sale was Chief of S&PL.

During the conduct of this study and the preparation of this report, COL Ernest D. Peixotto, CE, was Director of WES, and Mr. F. R. Brown was Technical Director.

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CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT

British units of measurement used in this report can be converted to metric units as follows:

Multiply	By	To Obtain
inches	2.54	centimeters
feet	0.3048	meters
pounds (mass) per cubic foot	16.0185	kilograms per cubic meter
pounds (force) per square inch	0.6894757	newtons per square centimeter
kips (force) per square inch	6,894.757	kilonewtons per square meter
feet per second	0.3048	meters per second
Fahrenheit degrees	5/9	Celsius or Kelvin degrees[a]

[a] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The U. S. Army Engineer Waterways Experiment Station (WES) conducted three different laboratory investigations under Defense Nuclear Agency (formerly Defense Atomic Support Agency) sponsorship in connection with the Diamond Mine Event, an underground test conducted at the Nevada Test Site. The WES studies were as follows: (1) determination of the effect of rate of loading on the laboratory constitutive properties of tuff, (2) development of an improved rock-matching grout, (3) evaluation of gage placement effects in a grout medium. This report is concerned with the study described in item 1.

Originally it was planned that the study would consist only of a series of static and dynamic uniaxial strain (UX) tests to determine rate effects on tuff for only the UX state. However, the UX test required tuff cores 4 or more inches[1] in diameter, and only a limited amount of material of this size was available for testing. Hence, only a limited picture of the rate effects in tuff were obtained. Since a supply of wire line NX-size (1-7/8-inch diameter) cores suitable for triaxial (TX) testing was also provided, it was decided to test these cores statically and dynamically in triaxial compression in order to examine the effect of loading rate for this second test condition.

1.2 PURPOSE

The purpose of this study was to determine the effect of variations in loading rate from static (approximately 2 minutes to peak stress) to dynamic (approximately 20 msec to peak stress) on the stress-strain properties of Diamond Mine tuff in UX and TX tests.

[1] A table of factors for converting British units of measurement to metric units is presented on page 7.

1.3 SCOPE

The main part of the study consisted of two static and three dynamic UX tests and two dynamic and four static TX tests. In addition, preliminary tests were conducted to examine the effects of processing and handling on the water content of the tuff specimens and to document the water content and density of the materials.

CHAPTER 2

PRELIMINARY INVESTIGATIONS

2.1 SAMPLE LOCATION

Figure 2.1 is a plan view of the area where the tuff cores tested at WES were obtained. The cores for the uniaxial strain (UX) tests were 6 inches in diameter and were taken at the cavity wall. The remaining cores were approximately 1.9 inches in diameter and were taken at various distances into the mass from the cavity wall. The cores arrived at WES on 23 February 1971. All the cores had been wrapped in foil and waxed for shipping. However, the wax was chipped around some of the cores, as noted in Figure 2.1.

2.2 MATERIAL DESCRIPTION

The material may be generally described as a medium- to coarse-grained altered volcanic rock containing broken feldspar and a zeolite matrix. The color varied from deep red to white.

Table 2.1 lists the wet unit weights (γ), water contents (w), and dry unit weights (γ_d) measured on pieces of the material in the condition as received by WES and after being exposed to air during trimming. Water content, as described in this report, is the ratio of weight of water to weight of dry material. Wet unit weight, γ, is the weight per unit volume of intact core and includes the weight of the preserved water. Dry unit weight, γ_d, is the weight per unit volume of the intact core in a dry state, and may be calculated from:

$$\gamma_d = \frac{\gamma}{1 + w}$$

An attempt was also made to determine the specific gravity of the material (i.e., the weight of solid particles per unit volume of the solid particles). One piece of core from Boring PI 1, located 0 to 1.5 feet from the cavity wall, was crushed and the volume of the

particles determined by water displacement. The specific gravity value measured was 2.34.

If it is assumed that the material, as received, is completely saturated, then the specific gravity may be calculated based on the measured water content and wet unit weight. The following list tabulates the calculated values:

Boring	Distance from Cavity Wall	Calculated Specific Gravity
	feet	
GGA 1	20.3-20.7	2.4[illegible]
PI 3	24.4-25.6	2.39
PI 4	24.0-26.0	2.38
GGA 3	24.1-26.6	2.38
	7.1-8.8	2.45

The above values would be numerically higher if the material was not saturated. Thus, the measured specific gravity of 2.34 for the Boring PI 1 core may be in error on the low side.

2.3 EFFECT OF HANDLING ON WATER CONTENT

Figure 2.2 presents the results of one test conducted on a large piece of tuff (1.9 inches in diameter) to determine the effect of oven drying time on the loss of water in the tuff. The plot indicates that a minimum oven drying time of 2 days is required for proper determination of water content for a specimen of that size. Most of the specimens were smaller and were subjected to a 3-day oven drying time. A test was then conducted to determine if the material was sensitive to rapid air drying after the foil and wax containers had been stripped. One piece of core was selected, quickly stripped of the wrapping, and broken into two pieces whose weights were obtained. One piece was placed in the oven, and the other was placed in a humid storage room. Figure 2.3 presents specimen weight versus time for the two pieces.

The results indicate that the material will lose water fairly rapidly even under very humid conditions and that core water will be lost from specimens during the necessary exposure for trimming even if the trimming is done in a humid room.

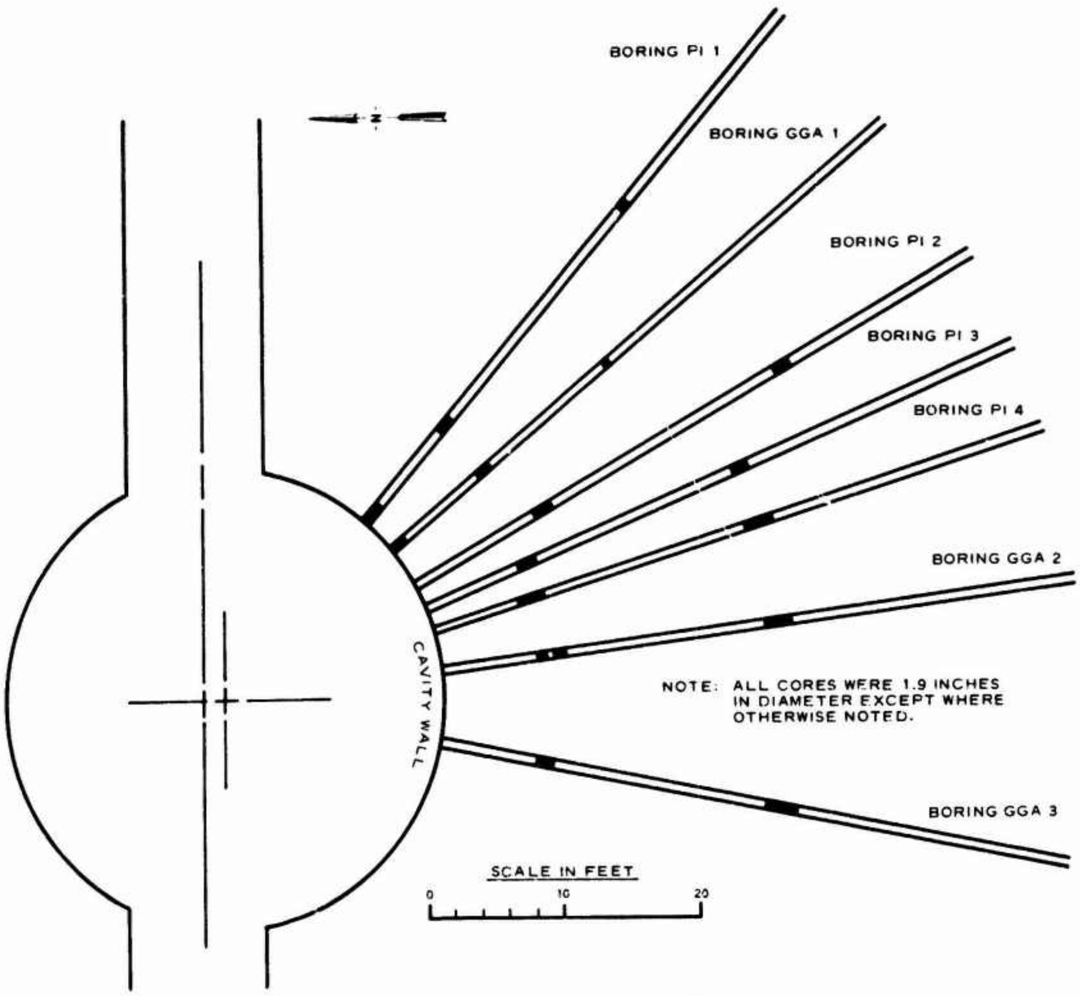
2.4 EFFECT OF MOISTURE ON PULSE VELOCITY

Two tests were conducted on the material to determine if water content influenced the laboratory compressional wave velocity at zero stress. The first specimen (PI 4) was trimmed and placed in water for a period of 20 hours. After this time, the velocity was measured. Unfortunately, because the weight was not determined after this soaking, the water content could only be estimated. The estimated initial water content was ≈22 percent. The specimen was then allowed to air dry, and again the velocity was recorded. Following this measurement, the specimen was weighed and placed in a drying oven. At various intervals, the specimen was taken from the oven, weighed, and the velocity measured. The results of measured velocity versus water content are plotted in Figure 2.4.

A specimen from Boring GGA 3 was also tested. Its velocity and weight were determined after trimming, after a 12-hour soaking, after 1-hour air drying, after another 12-hour soaking, and finally after oven drying for 12 hours. The results are also shown in Figure 2.4, and indicate that increasing water content could increase the compressional wave velocity when the specimen approaches saturation. The cause of the drop in velocity noted during oven drying is not understood.

TABLE 2.1 MEASURED WATER CONTENTS AND UNIT WEIGHTS DETERMINED ON A VARIETY OF THE TUFF MATERIAL RECEIVED BY WES

Boring	Distance of Core Location from Cavity Wall	Wet Unit Weight γ	Water Content w	Dry Unit Weight γ_d	Remarks
	feet	lb/cu ft	percent	lb/cu ft	
PI 1	0-1.5	115.1	17.5	98.0	Partially air dried during preparation
	0-1.5	119.1	18.4	100.6	Partially air dried during preparation
	0-1.5	--	--	--	$G_s = 2.34$
GGA 1	0-1.25	116.3	18.7	98.0	Partially air dried during preparation
	0-1.25	114.2	--	--	Partially air dried during preparation
	0-1.25	115.3	17.5	98.1	Partially air dried during preparation
	0-1.25	--	14.3	--	Air dried over 1 month
	20.3-20.7	119.0	24.2	95.8	As received
PI 2	10-11.5	--	25.0	--	As received
	10-11.5	114.6	--	--	Exposed during trimming
	10-11.5	117.9	--	--	Exposed during trimming
	10-11.5	--	20.1	--	Exposed during trimming
PI 3	7.9-8.9	--	25.2	--	As received
	7.9-8.9	--	22.3	--	Exposed during trimming
	7.9-8.9	117.1	--	--	Exposed during trimming
	7.9-8.9	117.3	22.5	95.8	Exposed during trimming
	24.4-25.6	119.2	22.0	97.7	As received
PI 4	6.5-7.5	--	24.5	--	As received
	6.5-7.5	--	18.8	--	Exposed and air dried during preparation
	6.5-7.5	--	18.5	--	Exposed and air dried during preparation
	7.5-8.5	--	--	96.1	Oven dried
	24.0-26.0	119.4	21.6	98.2	As received
GGA 2	8.1-8.5	113.4	--	--	Exposed and air dried during preparation
	23.9-24.8	--	21.3	--	As received
	24.8-25.9	--	21.9	--	As received
GGA 3	7.1-8.8	121.9	19.9	101.7	Exposed during trimming
	7.1-8.8	118.1	22.7	96.3	As received
	24.1-26.6	122.1	20.9	101.1	As received
	24.1-26.6	--	20.9	--	As received
	24.1-26.6	--	21.2	--	As received



DISTANCE, FT, OF CORE LOCATION FROM CAVITY WALL FOR INDICATED BORINGS

PI 1	GGA 1	PI 2	PI 3	PI 4	GGA 2	GGA 3
0 – 1.5[a]	0–1.25[a]	10.0–11.5[b]	7.4 – 7.9	6.5 – 7.5	7.0 – 7.8	7.1 – 8.8[b]
8.4 – 9.0	8.3 – 8.8	30.3–31.5[b]	7.9 – 8.9	7.5 – 8.5	8.1 – 8.5	24.1–26.6[b]
9.0 – 9.5	8.8 – 9.2		24.4–25.6[b]	24.0–26.0[b]	8.5 – 9.1	
28.8–29.4	20.3–20.7				23.9–24.8	
					24.8–25.9	

[a] 6-INCH-DIAMETER CORES.
[b] DAMAGED WAX AND OR SAMPLE BROKEN.

Figure 2.1 Plan view of area showing locations from which cores were taken.

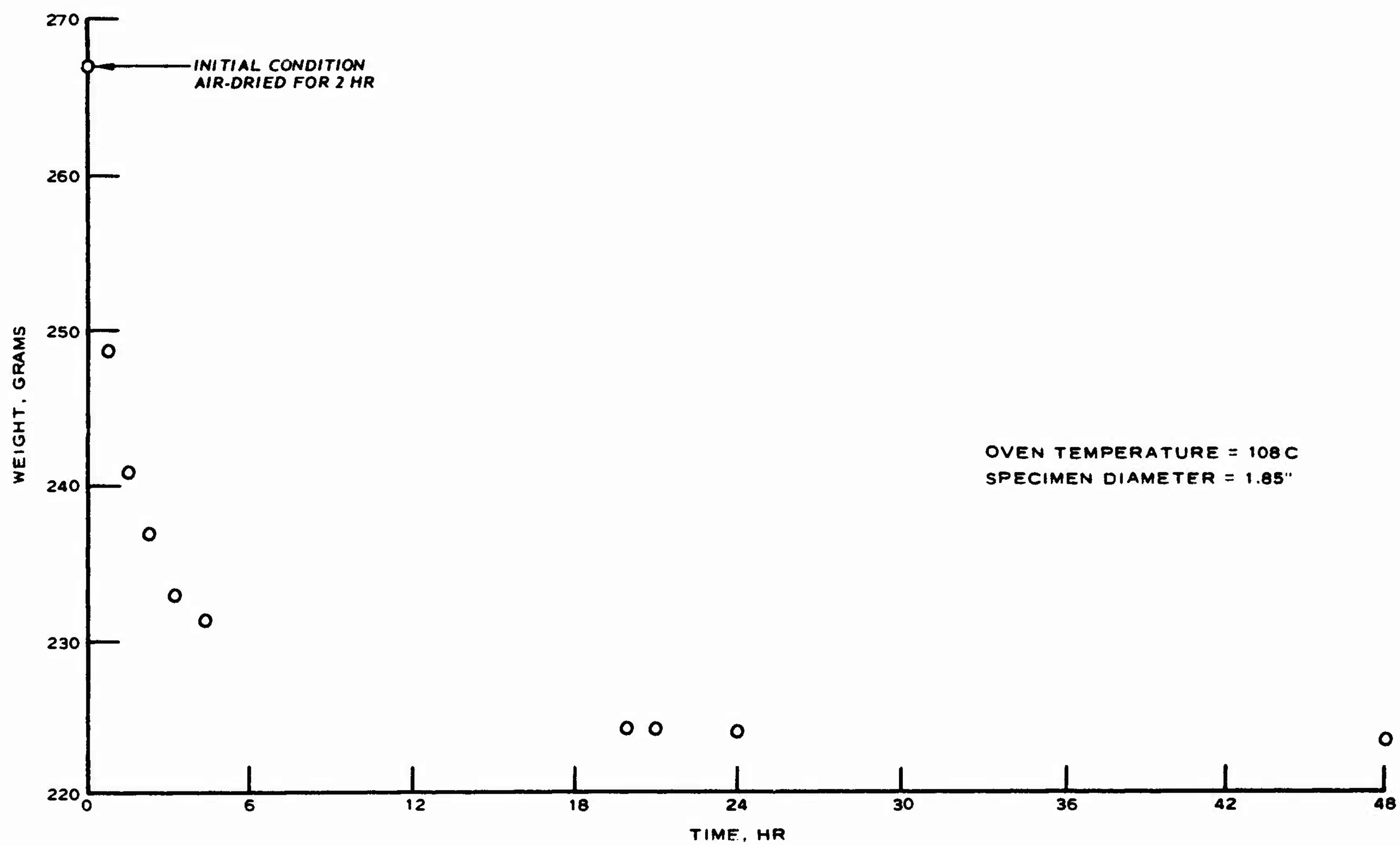


Figure 2.2 Specimen weight versus oven drying time for one piece of tuff.

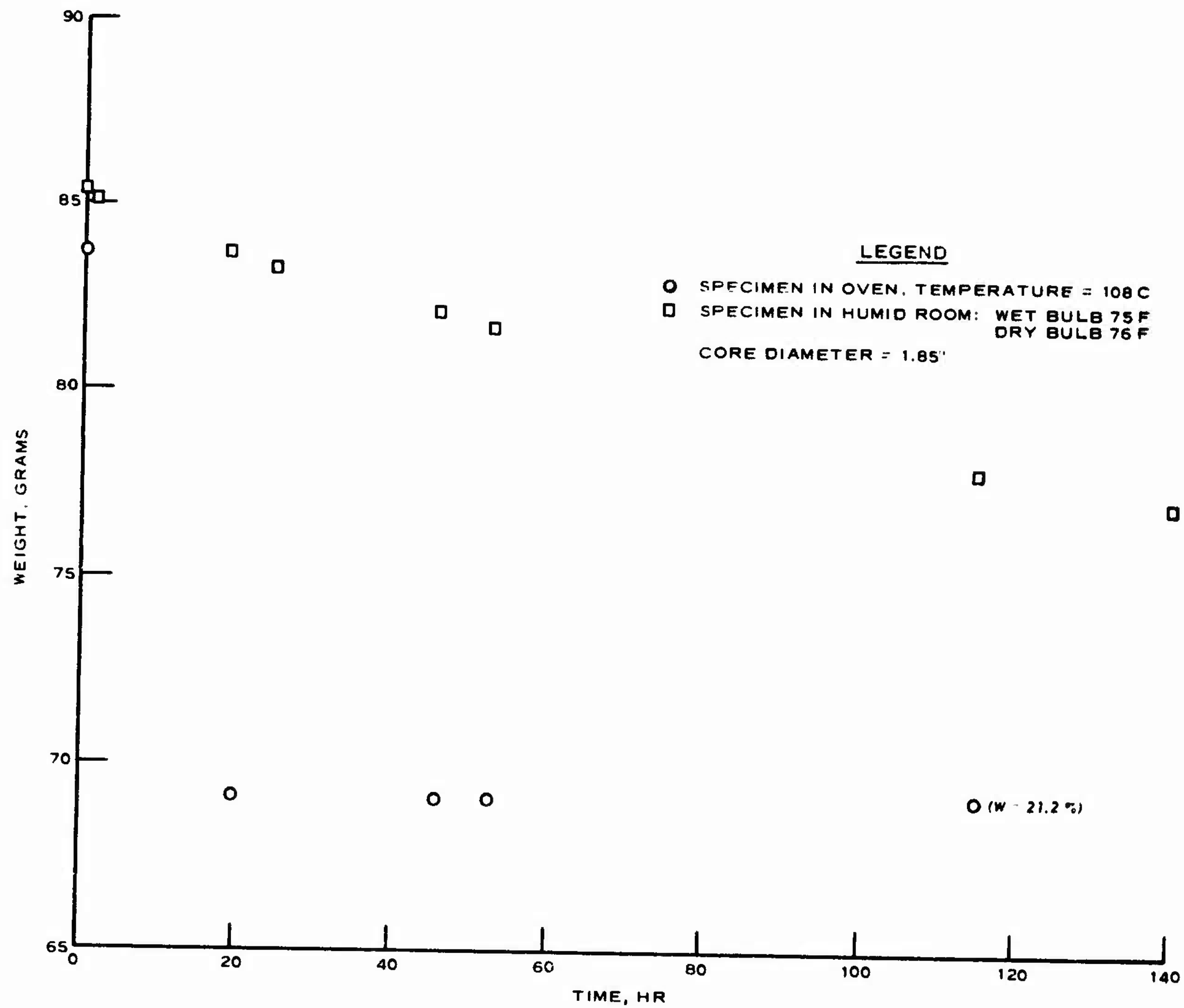


Figure 2.3 Specimen weight versus time for two pieces of tuff, one placed in an oven and one placed in a humid environment.

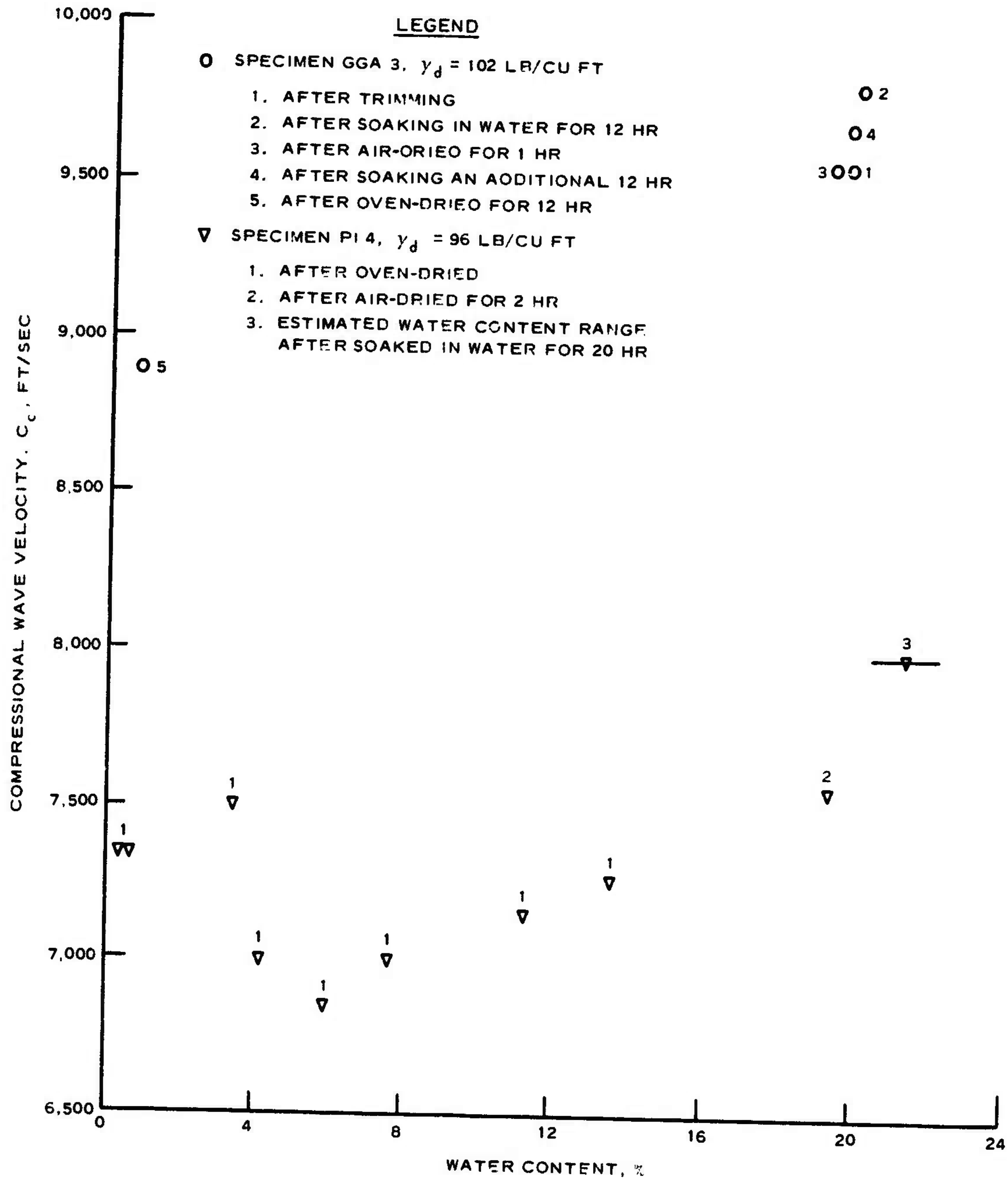


Figure 2.4 Compressional wave velocity versus water content for tests conducted on two pieces of tuff.

CHAPTER 3

CONSTITUTIVE PROPERTY TESTS

The laboratory testing program consisted of three types of tests conducted both statically (2 minutes to peak stress) and dynamically (20 msec to peak stress). Tests were conducted to pressures as high as 8 ksi. The types of tests included uniaxial strain tests and triaxial tests with hydrostatic and shear loading phases. In the uniaxial strain test, a wafer-shaped specimen is loaded in the vertical or axial direction while lateral expansion of the specimen is prevented. Applied axial pressure and axial specimen deformation are measured. A plot of the data as axial stress versus axial strain produces a curve whose slope is the constrained modulus, M . In the hydrostatic phase of the triaxial test, a cylindrical specimen is loaded by the same pressure in all directions while the axial and lateral specimen deformations are measured. A plot of the data in the form of pressure versus volumetric strain produces a curve whose slope is the bulk modulus, K . The triaxial shear phase can be conducted following the hydrostatic test. Once the peak hydrostatic pressure is reached, it is held constant. The specimen is then loaded further in the axial direction until the specimen can no longer support additional load. Measurements of this additional stress, the deviator stress $(\sigma_a - \sigma_r)$, and of the specimen's axial deflection can be plotted as deviator stress versus axial strain. The slope of the curve is Young's modulus, E . In addition, the peak deviator stress values from several tests conducted at various levels of confining pressure can be used to define a Mohr failure envelope or a yield surface expressed as a plot of $(\sigma_a - \sigma_r)$ versus P . It should be noted that the axial direction of the specimen in this testing program was taken along the axis of the field core. These cores were drilled radially out from the tunnel cavity along a horizontal plane.

3.1 SPECIMEN PREPARATION

The tuff specimens used in the laboratory testing program were prepared through the use of two different techniques because of the

difference in the specimens sizes required for the uniaxial strain tests and the triaxial tests. The specimens used in the triaxial tests were selected from the 1.9-inch-diameter field cores. Water content determinations were made on core fragments. The cores were then cut to lengths of approximately 5 inches on a diamond saw. The waste ends were laid aside while the specimen was lapped to produce smooth perpendicular ends. A thin rubber membrane was placed around each specimen, and the specimen was then placed in the triaxial chamber. The waste ends were then used for water content determinations. Precautions were taken to preserve the original water content of the cores. However, losses of greater than 2 percent were often noted, and losses of 6 percent were noted in specimens that were unusually difficult to trim and hence were exposed for a longer period of time. Some of the cores appeared to be very sensitive to lateral clamping, as evidenced by the fact that several cores sheared while being placed in the saw.

The specimens used for the uniaxial strain tests were prepared from the 6-inch-diameter cores. The cores were lathed to 4-inch-diameter by 3-inch-long specimens. The specimens were then slipped into 2-1/2-inch-long, 0.63-inch-thick steel rings of the same inside diameter (4.000 inches). The rings were expanded slightly by heating them in boiling water. The expanded rings were slipped over the specimens and allowed to cool, thus producing a "shrink fit." Once in the rings, the specimens were lathed on each end to produce a specimen height of 2-1/2 inches. As with the triaxial specimens, some core was lost due to breakage. Because of the trimming technique used, the specimens lost excessive water (more than 6 percent). No attempts were made to replace the lost water since it was not known if the water could be replaced uniformly throughout a specimen and since there were not enough specimens for the experimentation necessary to develop techniques. Table 3.1 lists all the specimens used in the testing program and presents the water contents and densities.

The uniaxial strain specimens had an average moisture content of 18 percent. The triaxial specimens had higher water contents (average of approximately 22 percent) and, therefore, probably more closely

represented the in situ material. It is believed that the test results from the UX and TX tests cannot be directly compared since water content differences could affect the stress-strain response of the material.

3.2 UNIAXIAL STRAIN TEST RESULTS

Five tests were conducted on tuff from Borings PI 1 and GGA 1, located at the cavity wall. Due to the trimming and preparation techniques employed, the average water content measured was 18 percent. Test PI 1.2 was a static test cycled at several levels of axial stress. Each loading required about 2 minutes. When the peak axial stress of each cycle was reached (i.e., prior to unloading), the stress was held for about 1 minute and then the unloading was initiated. The unloading was completed in about 1 second.

The test results are shown in Figure 3.1 as a plot of axial stress versus axial strain. Very little creep occurred at the first two lower stresses, but at the two higher stress levels some creep at peak stress was noted. If cycling did not influence behavior at stress levels above the cycled stress, then the peak points describe the virgin curve. For this material, the curve appears to soften slightly at axial stress levels above 7 ksi. Above that stress, the material also appears to creep under constant loadings. The results of Test PI 1.A are shown in Figure 3.2. This test was a dynamic test, and the plot of applied axial stress versus time is shown as an insert in Figure 3.2. The specimen was loaded to peak stress in 15 msec, after which the stress was held constant for 25 msec and then decayed in 70 msec. Of interest are (1) continued straining of the specimen during the period of constant stress, and (2) the softening of the stress-strain curve above a stress of 7 ksi. Figure 3.3 is a combination plot for Tests PI 1.2 and 1.A.

All of the uniaxial stress tests were conducted starting at atmospheric pressure. In the field, however, the tuff is under some pressure due to the material overburden. Figure 3.4 presents the same test data as Figure 3.3, but the data have been rezeroed to reflect an assumed overburden stress of 500 psi. For clarity, the unloading-reloading portions of the curves have been omitted. Although little difference is

seen at stresses below 5 ksi, the curves tend to deviate at higher stress levels.

The results of uniaxial shear Test GGA 1.A are shown in Figure 3.5. The specimen was loaded with a time to peak stress of 25 msec, and the decay time was 80 msec. The curve tends to soften at about 7 ksi, and only slight creep at peak stress is noted.

Uniaxial shear Test GGA 1.2 was a static test, but the membrane protecting the specimen from the fluid used to apply the load leaked at 1.3 ksi. Therefore, the results beyond that level are not considered valid. The test results are shown in Figure 3.6.

Figure 3.7 presents a plot of axial stress versus axial strain measured in uniaxial strain Test GGA 1.3. The peak pressure was reached in 40 msec, held constant for 15 msec, and decayed in 60 msec. The curve tends to soften at a lower stress (about 5 ksi) than those for the other tests. A combination plot of the data for Tests GGA 1.A, 1.2, and 1.3 is shown in Figure 3.8. Again, the data were rezeroed to reflect an assumed 500-psi overburden pressure, and the resulting curves are shown in Figure 3.9.

An attempt was made to monitor the radial stress required to maintain a condition of no radial strain in the uniaxial strain tests. Strain gages were placed on the outsides of the 1/2-inch-thick steel rings containing two of the tuff specimens, Specimens GGA 1.2, and PI 1.A. As vertical stresses were applied to the specimens, the output of the gages was monitored. Thick-wall cylinder equations from theory of elasticity and the measured outside circumferential strains were used to calculate the inside radial stresses. Obviously, some movement occurs inside the rings; hence, a true no-radial-strain condition does not exist. At the maximum loadings of the two tests conducted, the calculated radial strain was 28 μin/in. The axial stress versus axial strain results have been presented previously. The axial stress-radial stress results are presented in Figure 3.10 as a plot of deviator stress (σ_a - σ_r) versus mean normal stress (P). The membrane protecting Specimen GGA 1.2 leaked during loading, but the test results tend to substantiate the accuracy of the calculated radial stress values since, after

the leak, the radial stress should have become equal to the axial stress and the deviator stress should have become zero. This is what appears to have occurred in the test. The results of dynamic Test PI 1.A appear questionable at low pressures since the output from the strain gages was near the lower limit of accuracy of the recording equipment. Also, the test was conducted from atmospheric pressure, and the specimen's previous overburden stress state, which is unknown, could have influenced the results at the low stress levels. The data above 1 ksi mean normal stress appear to be reasonable.

3.3 TRIAXIAL TEST RESULTS (HYDROSTATIC PORTION)

The results of the hydrostatic loading phase of five triaxial tests on tuff specimens are shown in Figure 3.11 as a plot of pressure versus volumetric strain. The type test (static or dynamic) is indicated on the plot and, in the case of the dynamic tests, the time to peak pressure is also shown. Five hydrostatic loading tests were conducted. In each of the tests except Test PI 4.1, the hydrostatic phase of the triaxial test was stopped at the peak pressure, and a triaxial shear test conducted. The membrane protecting Specimen PI 4.1 leaked at 7 ksi. Therefore, the results beyond that pressure are invalid and are not shown. The membrane protecting Specimen PI 2.1 also leaked. A drop of the oil used as the confining fluid in the test was found on the specimen at the end of the shear test. The leak may have occurred during either the hydrostatic or shear phase of the test. Therefore, data for the hydrostatic phase of Test PI 2.1 should be regarded with some suspicion.

All the hydrostatic pressure loadings were conducted from atmospheric pressure. Therefore, the data for the plots in Figure 3.11 were rezeroed to some pressure level reflecting field conditions, since the strains measured below a stress level reflecting those conditions would not be representative of the response of the in situ material. Figure 3.12 shows the hydrostatic test results plotted to reflect the assumed 500-psi initial in situ hydrostatic state of stress. It should be noted that some of the material in the field immediately surrounding

the cavity would have undergone stress relief to some extent. Therefore, the rezeroed curves in Figure 3.12 represent only the material response at some distance from the cavity (assuming that the in situ stress state of 500 psi is valid).

3.4 TRIAXIAL TEST RESULTS (SHEAR PORTION)

Three static and two dynamic tests were conducted at confining pressures ranging from 0 to 6 ksi. The results of these tests are shown in Figure 3.13 as plots of deviator stress versus axial strain. Although Specimen PI 2.2 was unloaded prior to failure, extrapolation of the stress-strain curve indicated that a maximum deviator stress of about 6.5 ksi could be expected. It is doubtful that the data for Test PI 2.1 are valid because of the leakage mentioned previously. Because Test GGA 2 was an unconfined compression test, the large strain that occurred with increasing deviator stress appears reasonable. The data for Tests PI 3.1 and 3.2 and PI 2.2 also appear reasonable. It is not known if the observed increase in Young's modulus resulted from the increase in the level of confining pressure or from rate of loading effects or from a combination of both.

If the maximum deviator stress at failure for the specimens is plotted versus the mean normal stress at failure, a failure envelope can be described. Figure 3.14 is such a plot. Although more tests are required to better define the envelope, the data indicate a flattening of the envelope at pressures above 3 ksi.

TABLE 3.1 WATER CONTENTS AND UNIT WEIGHTS OF TEST SPECIMENS

Boring	Distance from Cavity Wall	Specimen Test No.	Water Content W	Wet Unit Weight γ	Dry Unit Weight γ_d	Remarks
	feet		percent	lb/cu ft	lb/cu ft	
Uniaxial Strain Test Specimens:						
PI 1	0-1.5	PI 1.A	17.5	115.1	98.0	Exposed to air for several hours
		PI 1.2	18.4	119.1	100.6	Exposed to air for several hours
GGA 1	0-1.25	GGA 1.A	18.7	116.3	98.0	Exposed to air for several hours
		GGA 1.2	--	114.2	--	Lost due to leak
		GGA 1.3	17.5	115.3	98.1	Exposed to air for several hours
Triaxial Strain Test Specimens:						
PI 2	10.0-11.5	--	25.0	--	--	As received
		--	20.1	--	--	Piece exposed 1 hour during trimming of specimens
		PI 2.1	--	114.6	--	As tested
		PI 2.2	--	117.9	--	As tested
PI 3	7.9-8.9	--	25.2	--	--	As received
		--	22.3	--	--	Piece exposed 1 hour during trimming of specimens
		PI 3.1	--	117.1	--	As tested
		PI 3.2	22.5	117.3	95.8	As tested
PI 4	6.5-7.5	--	24.5	--	--	As received
		--	18.8	--	--	Pieces exposed 2 hours during trimming of specimens (difficult to trim)
		PI 4.1	18.5	--	--	Loss due to leak
GGA 2	8.1-8.5	--	--	113.4	--	Exposed about 2 hours during trimming

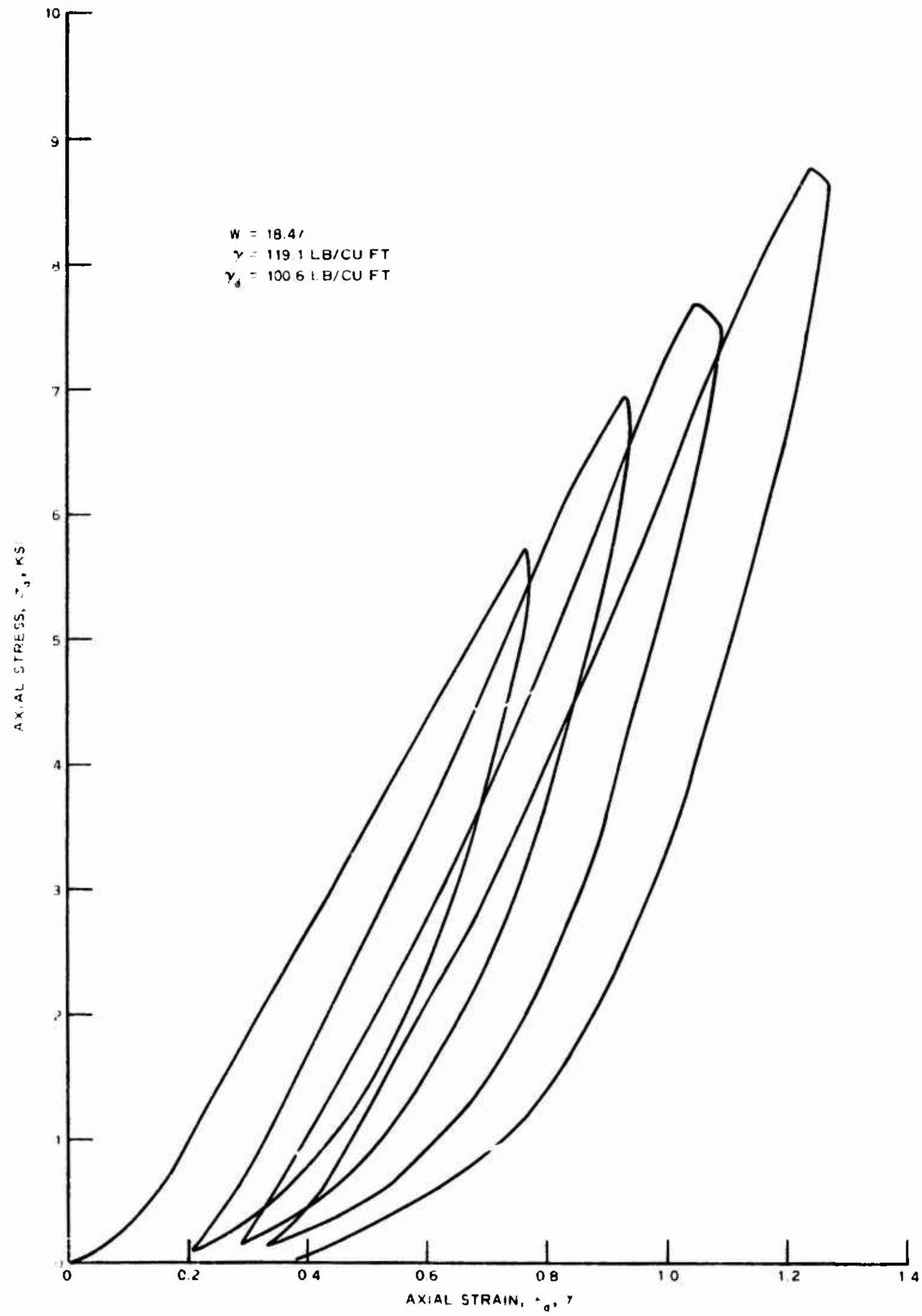


Figure 3.1 Results of static uniaxial strain Test PI 1.2.

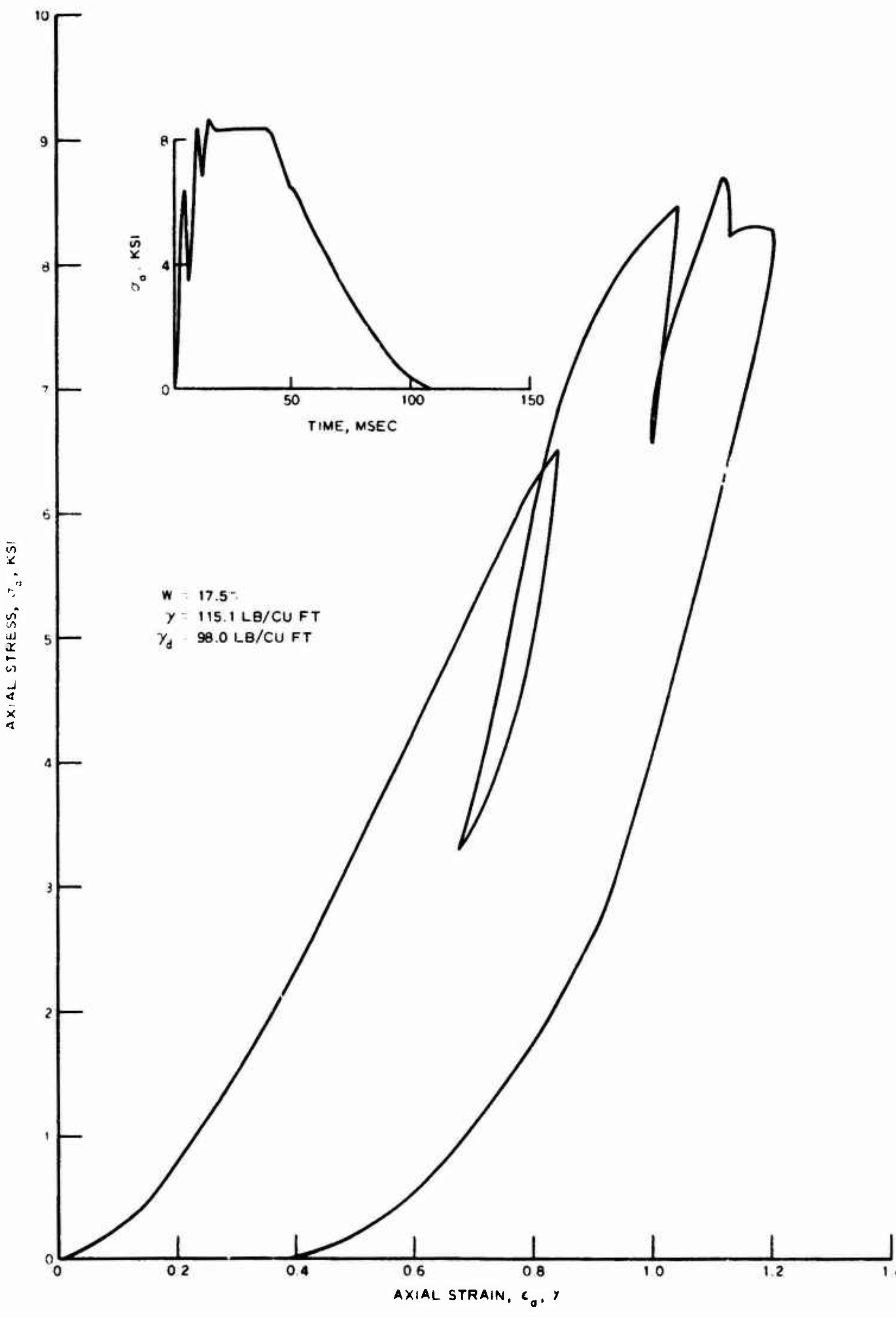


Figure 3.2 Results of rigid boundary dynamic uniaxial strain Test PI 1.A.

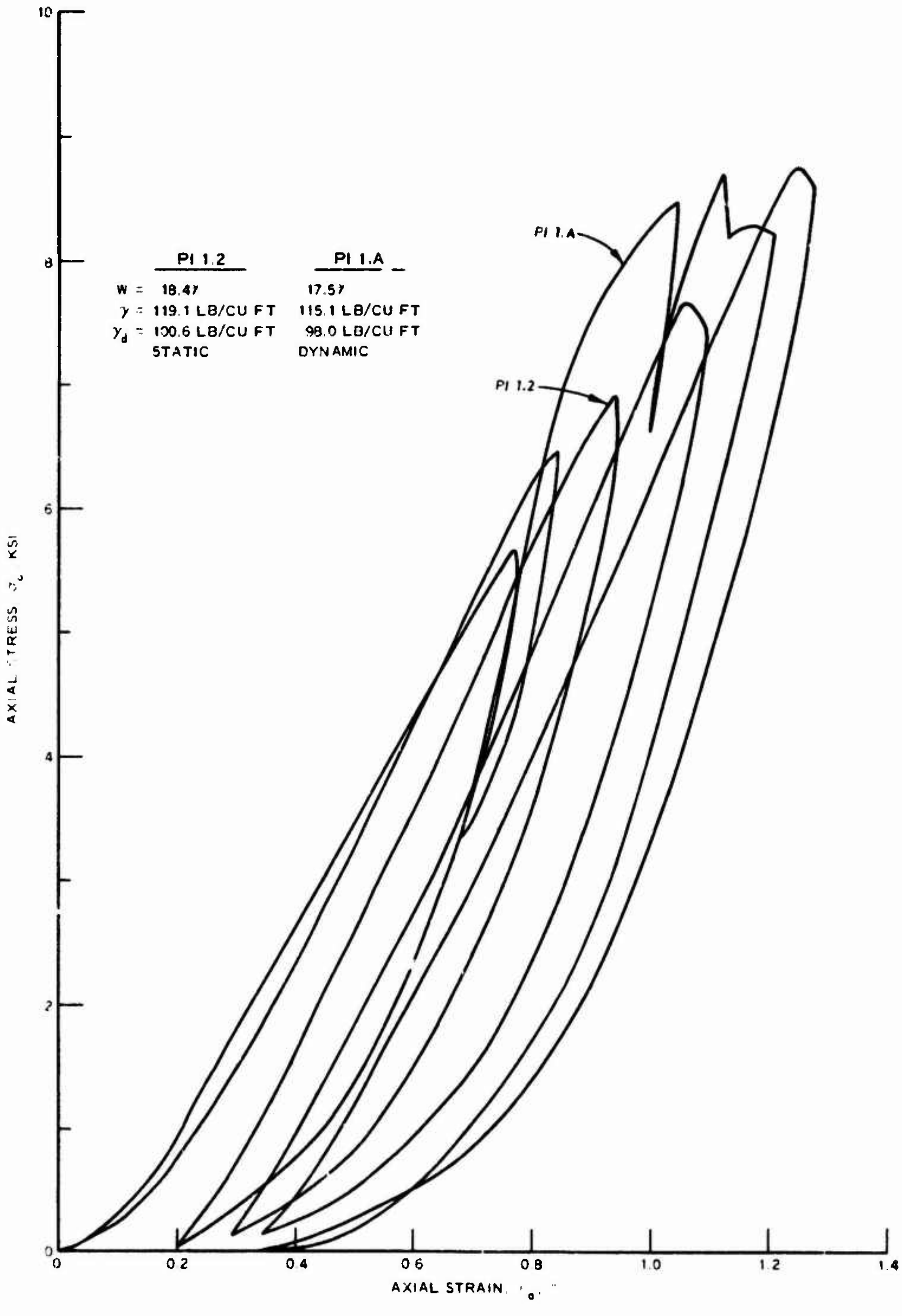


Figure 3.3 Comparison of results of uniaxial stress Tests PI 1.2 and 1.A.

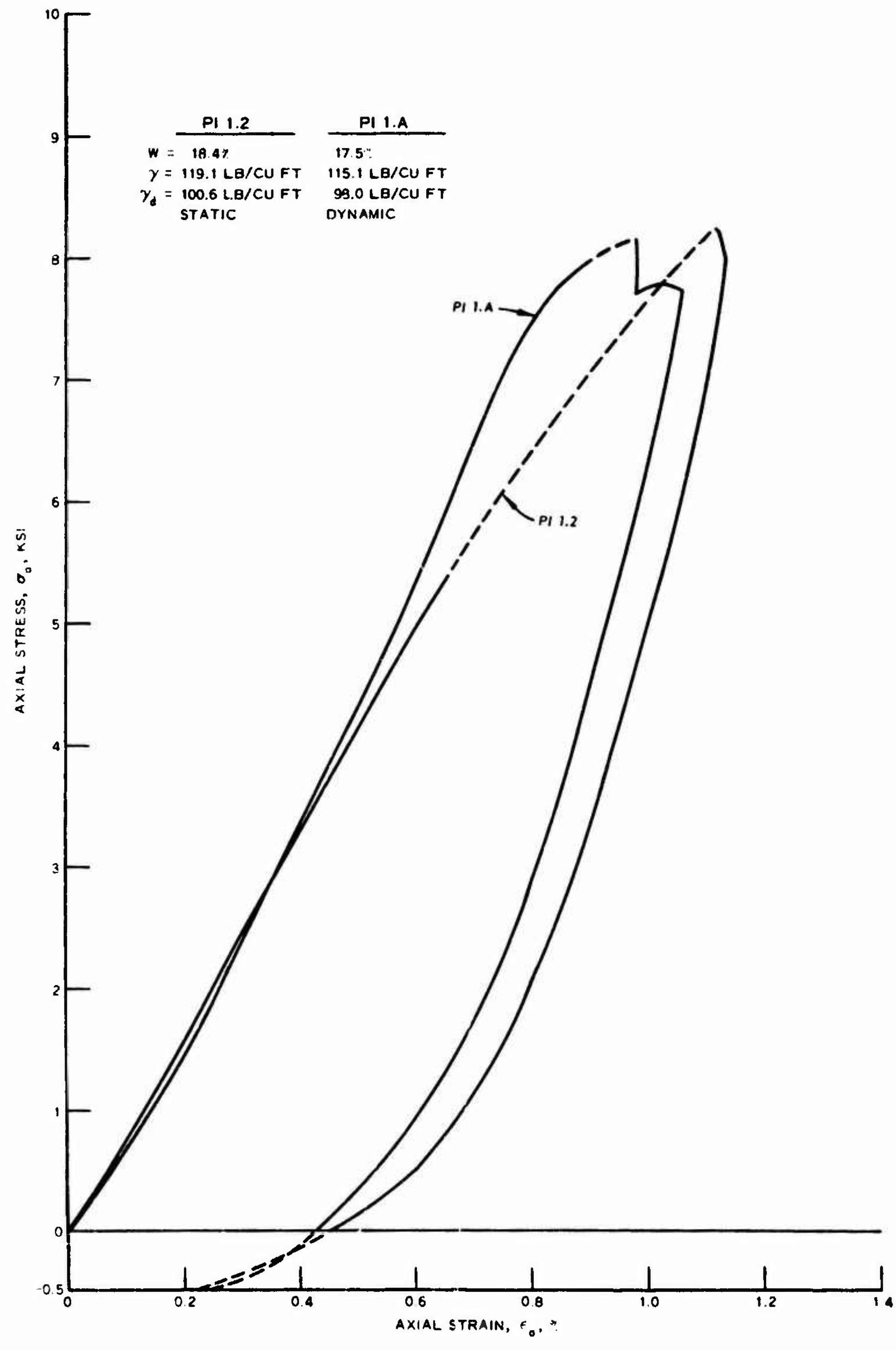


Figure 3.4 Comparison of results of uniaxial strain Tests PI 1.2 and 1.A with data rezeroed to reflect assumed overburden pressure of 500 psi.

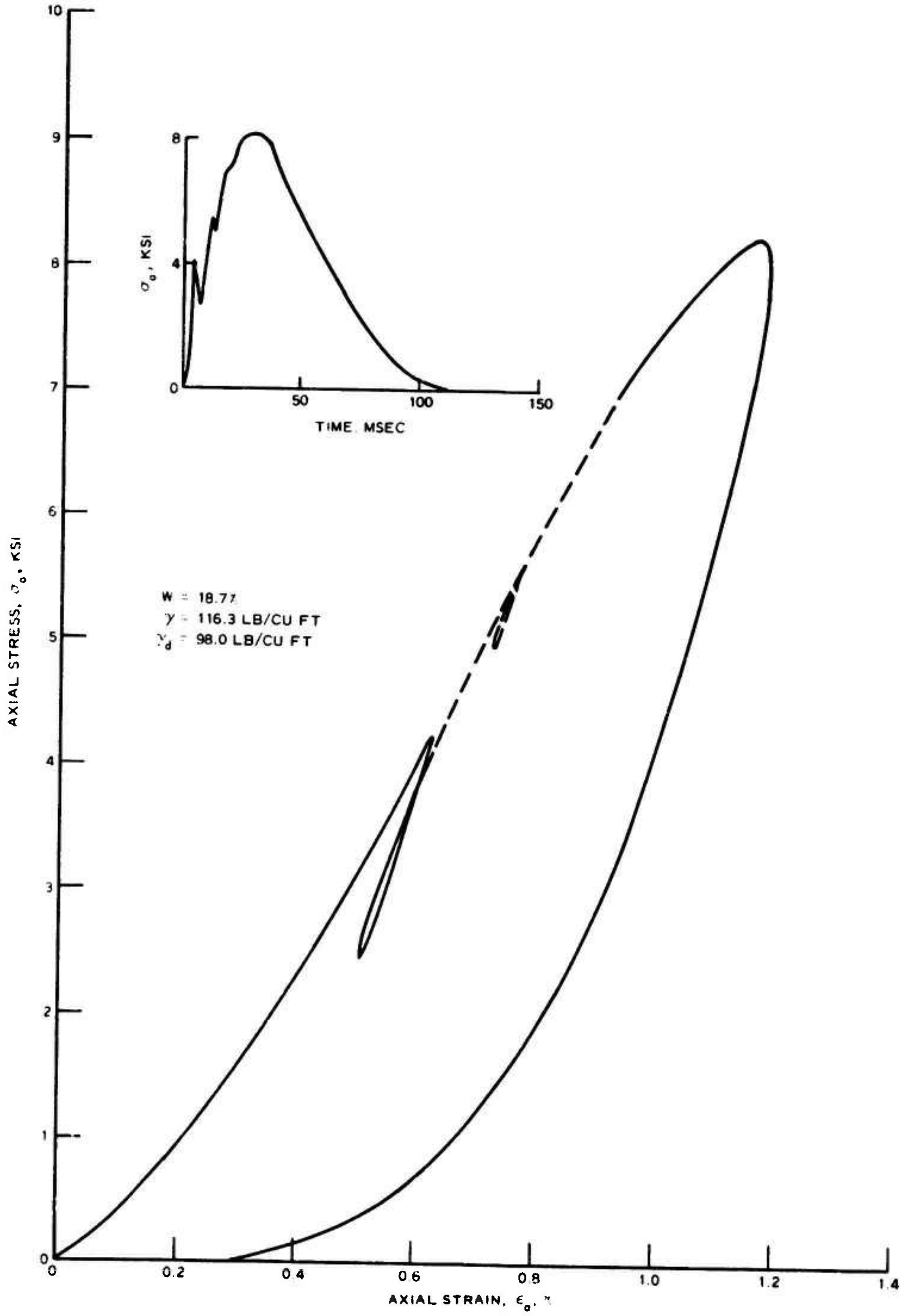


Figure 3.5 Results of rigid boundary dynamic uniaxial strain Test GGA 1.A.

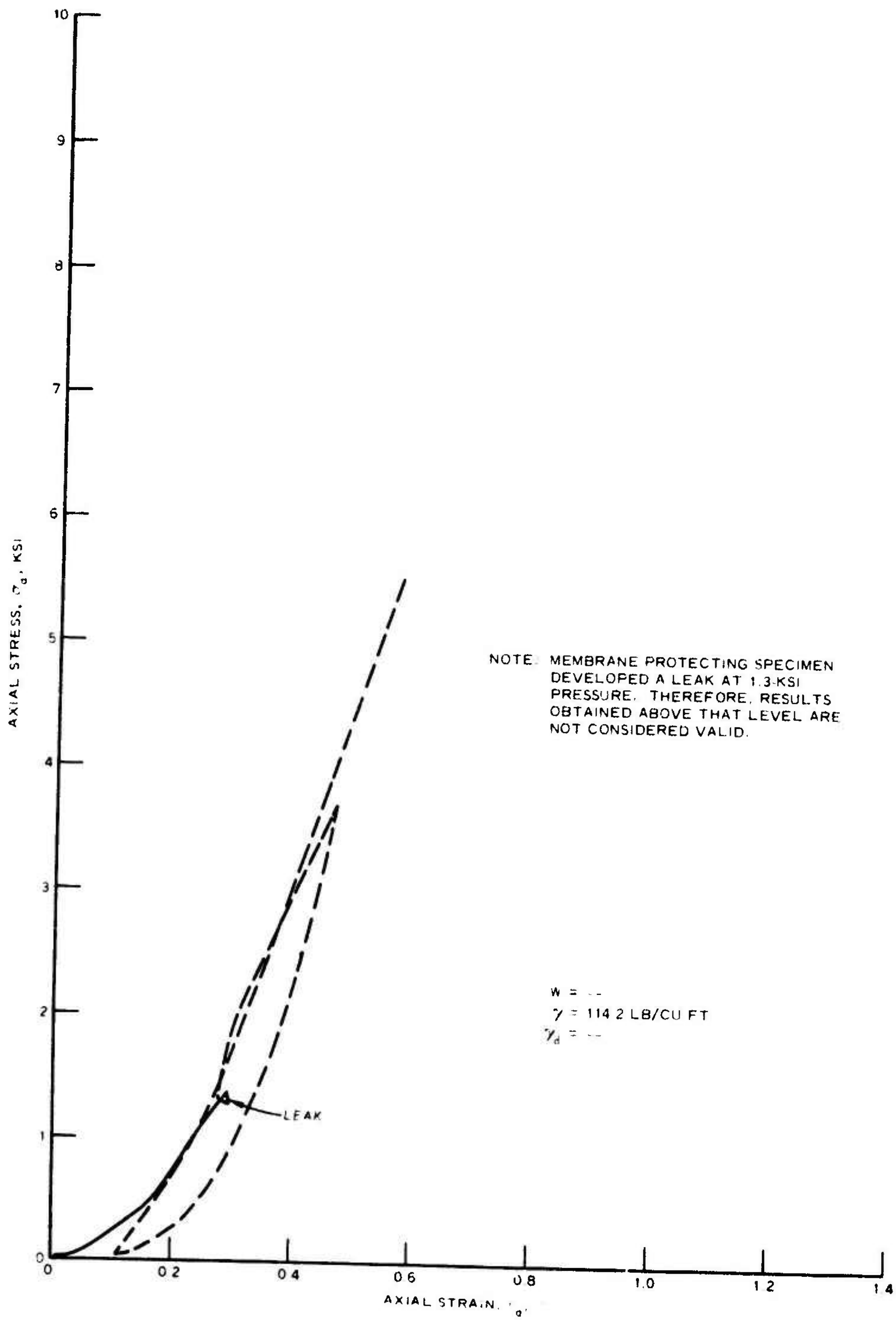


Figure 3.6 Results of static uniaxial strain Test GGA 1.2.

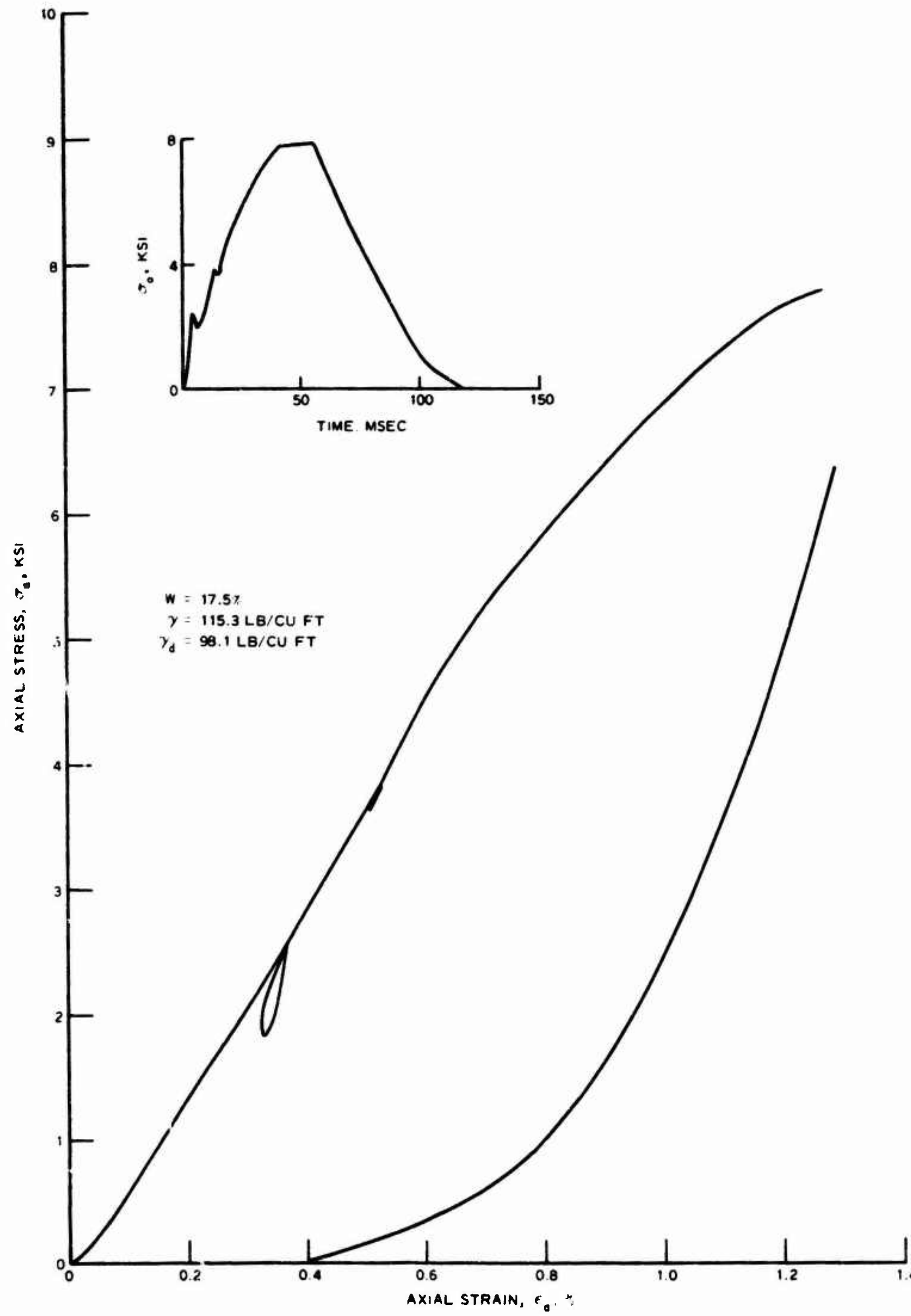


Figure 3.7 Results of rigid boundary dynamic uniaxial strain Test GGA 1.3.

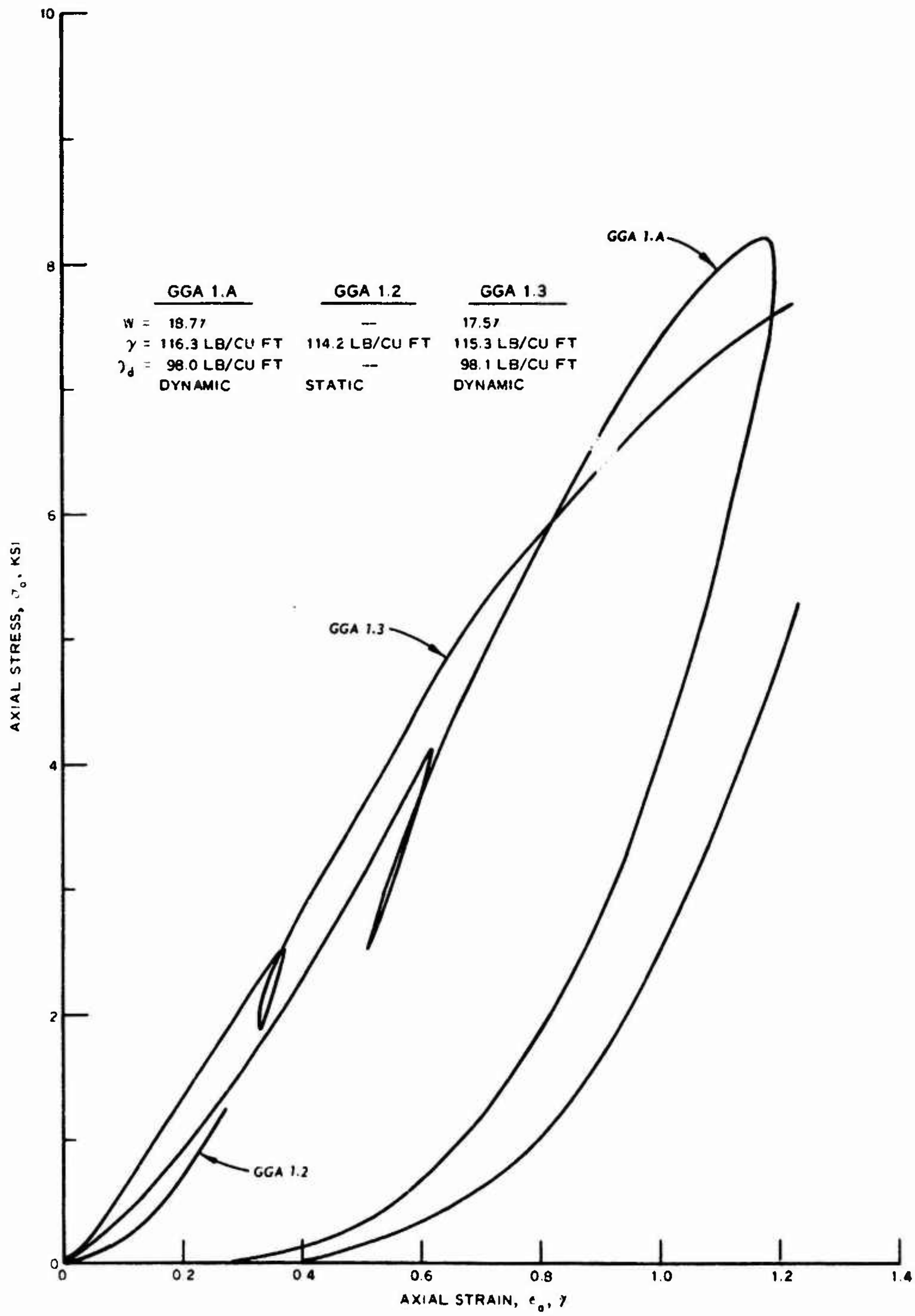


Figure 3.8 Comparison of results of uniaxial strain Tests GGA 1.A, 1.2, and 1.3.

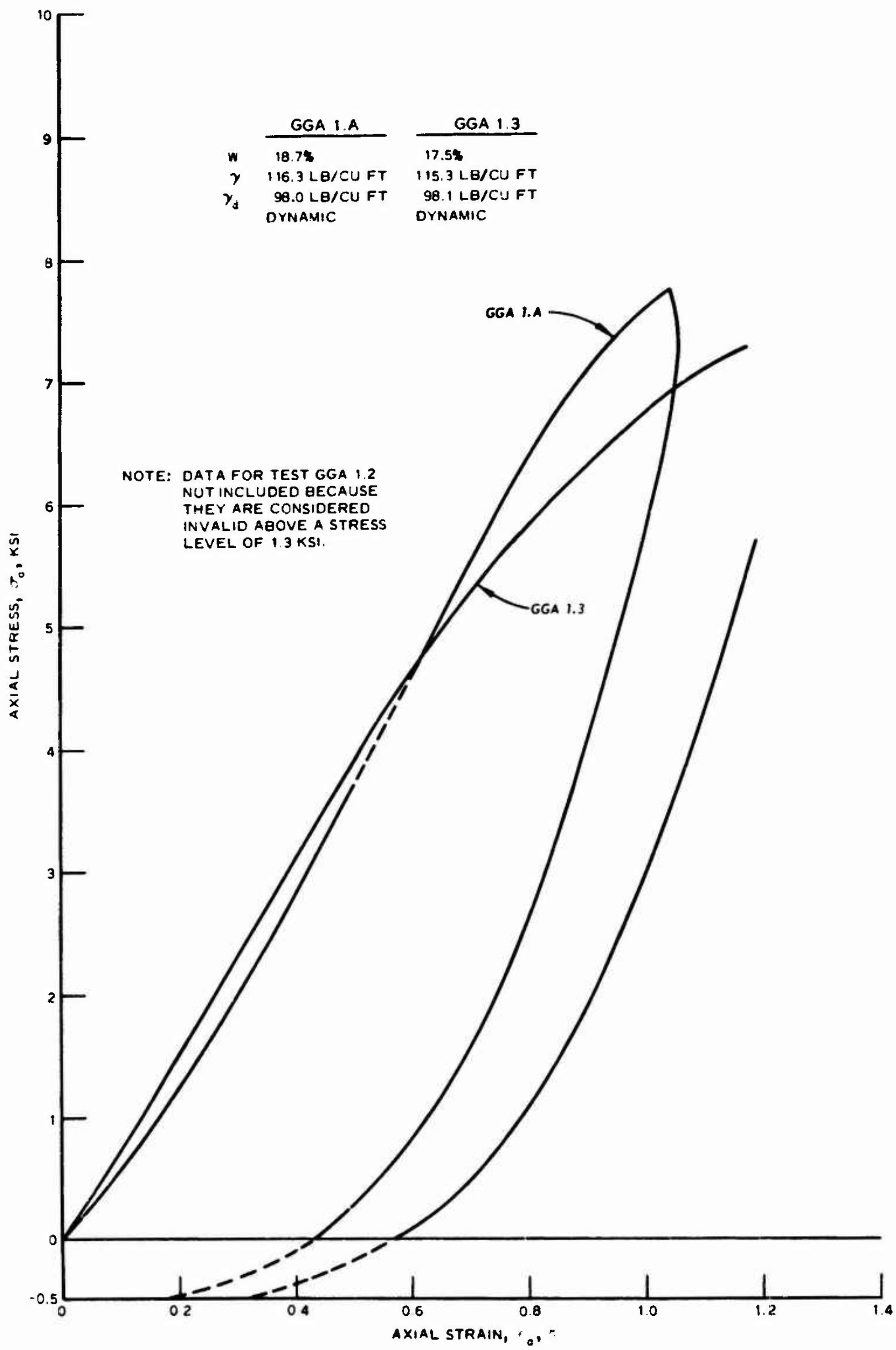


Figure 3.9 Comparison of results of uniaxial strain Tests GGA 1.A and 1.3 with data rezeroed to reflect assumed overburden pressure of 500 psi.

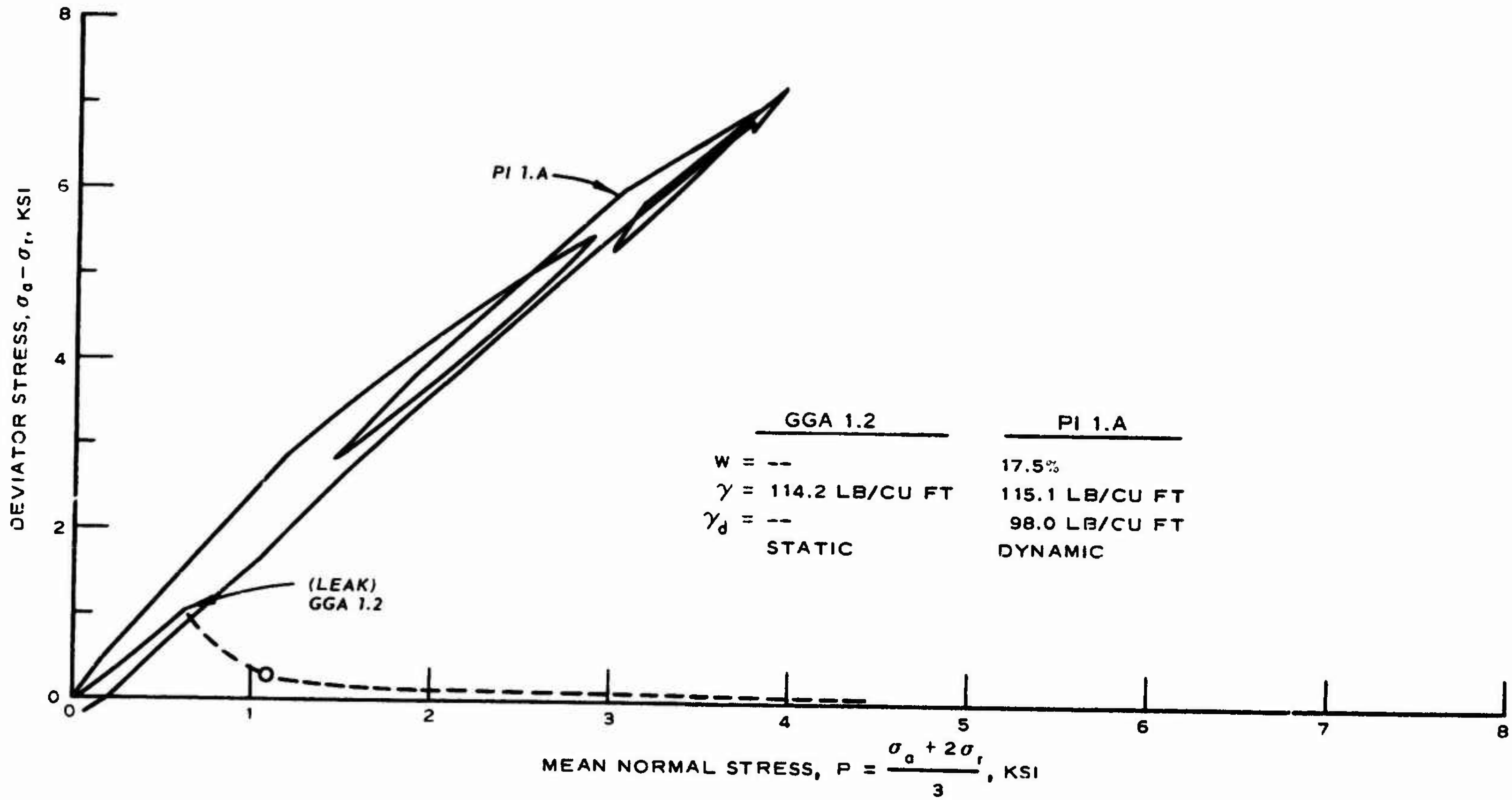


Figure 3.10 Calculated stress paths of uniaxial strain Tests GGA 1.2 and PI 1.2 with strain-gaged confining rings.

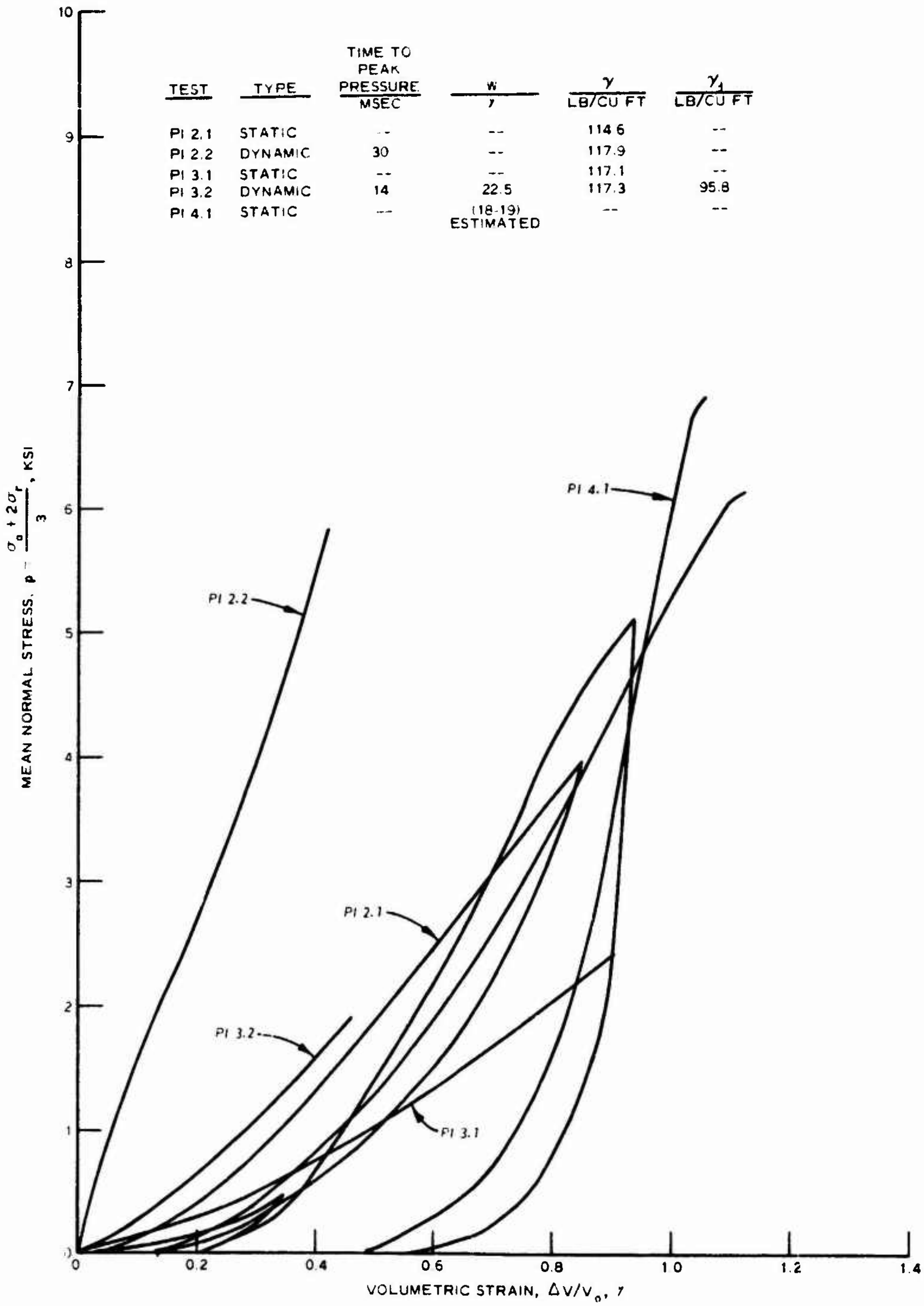


Figure 3.11 Comparison of results of static and dynamic hydrostatic Tests PI 2.1, 2.2, 3.1, 3.2, and 4.1.

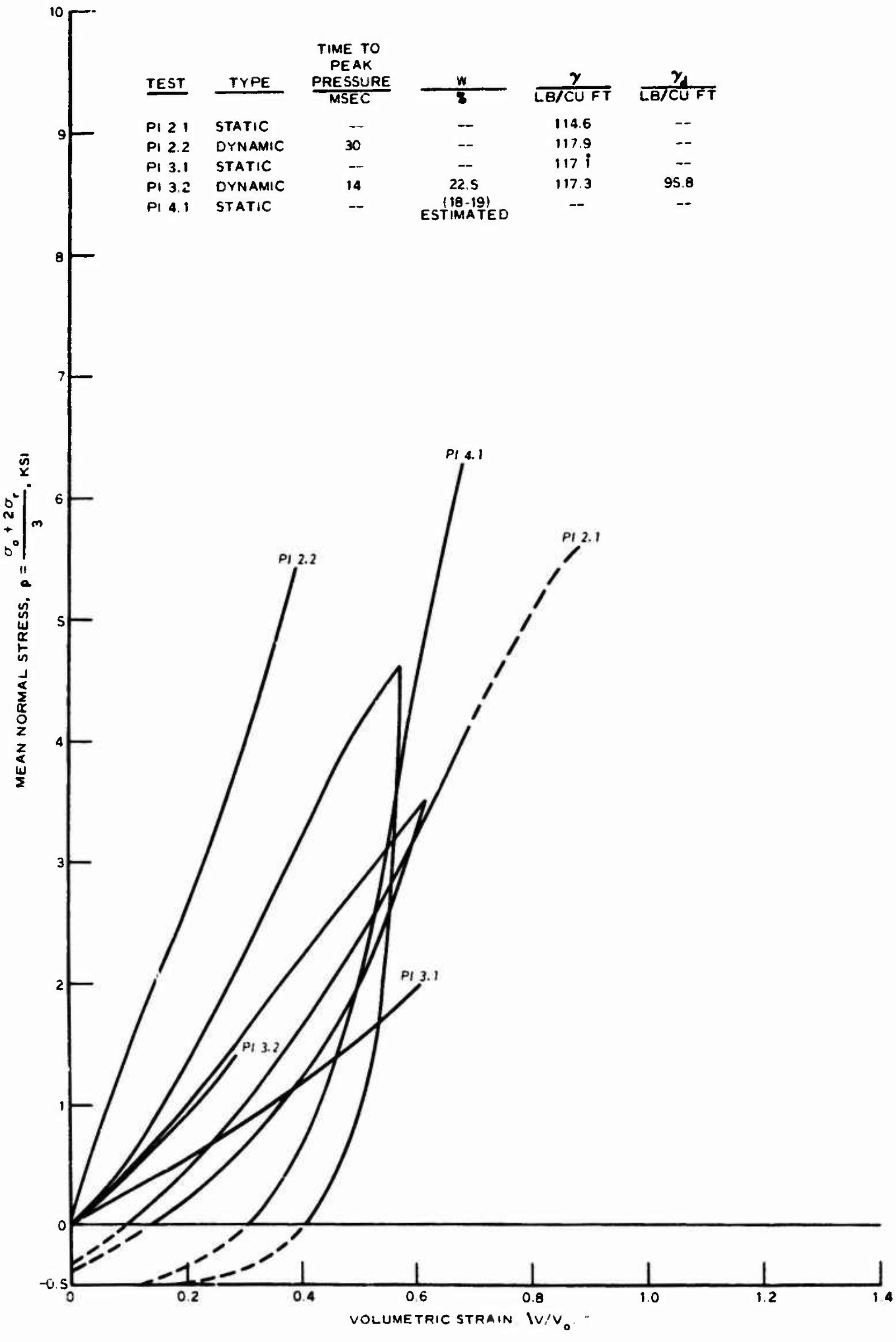
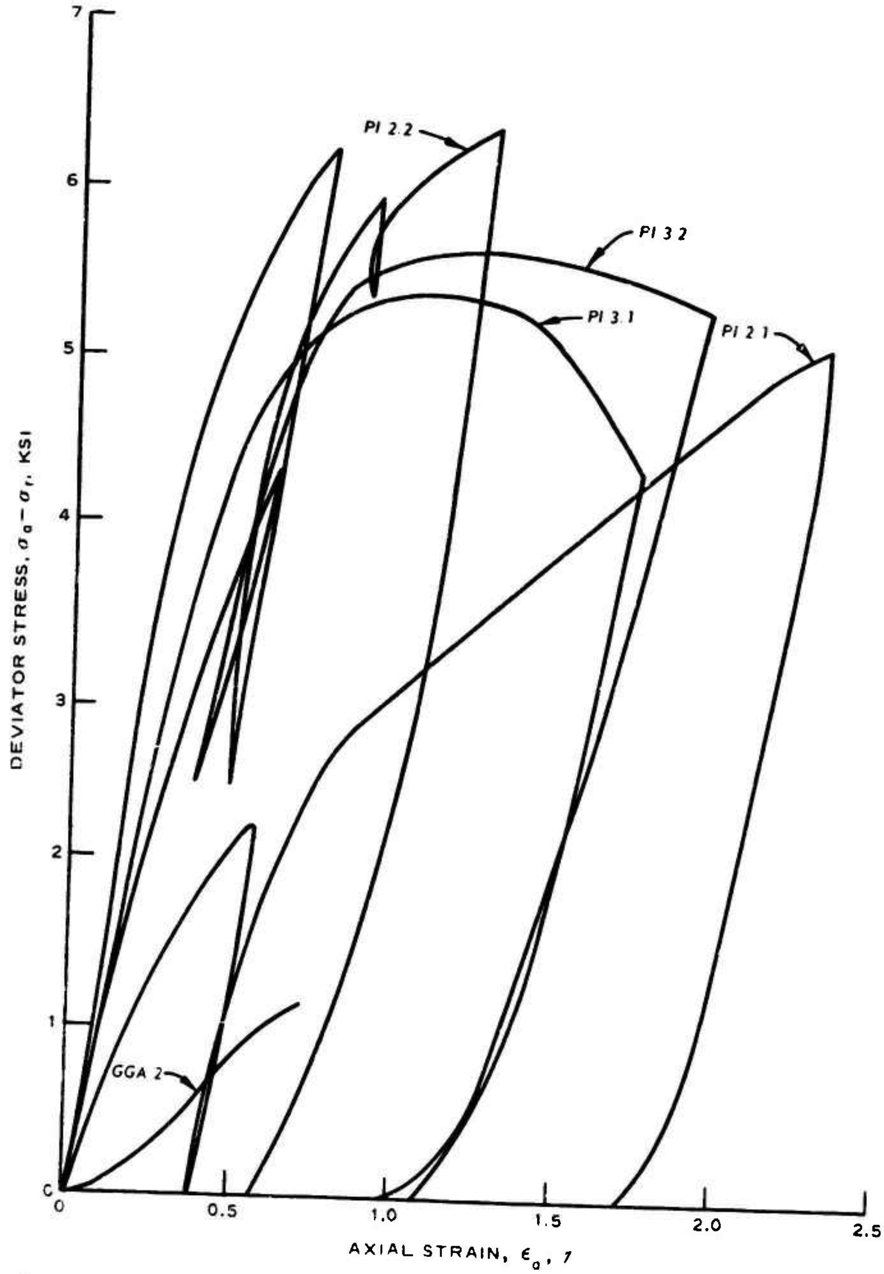


Figure 3.12 Comparison of results of static and dynamic hydrostatic Tests PI 2.1, 2.2, 3.1, 3.2, and 4.1 with data rezeroed to reflect assumed overburden pressure of 500 psi.



TEST	TYPE	CONSTANT σ_r KSI	TIME TO PEAK PRESSURE MSEC	W %	γ LB/CU FT	γ_d LB/CU FT
GGA 2	STATIC	0	--	--	113.4	--
PI 2.1	STATIC	6.23	--	--	114.6	--
PI 2.2	DYNAMIC	5.87	21	--	117.9	--
PI 3.1	STATIC	2.48	--	--	117.1	--
PI 3.2	DYNAMIC	1.97	24	22.5	117.3	95.8

Figure 3.13 Comparison of results of static and dynamic triaxial shear Tests GGA 2, and PI 2.1, 2.2, 3.1, and 3.2.

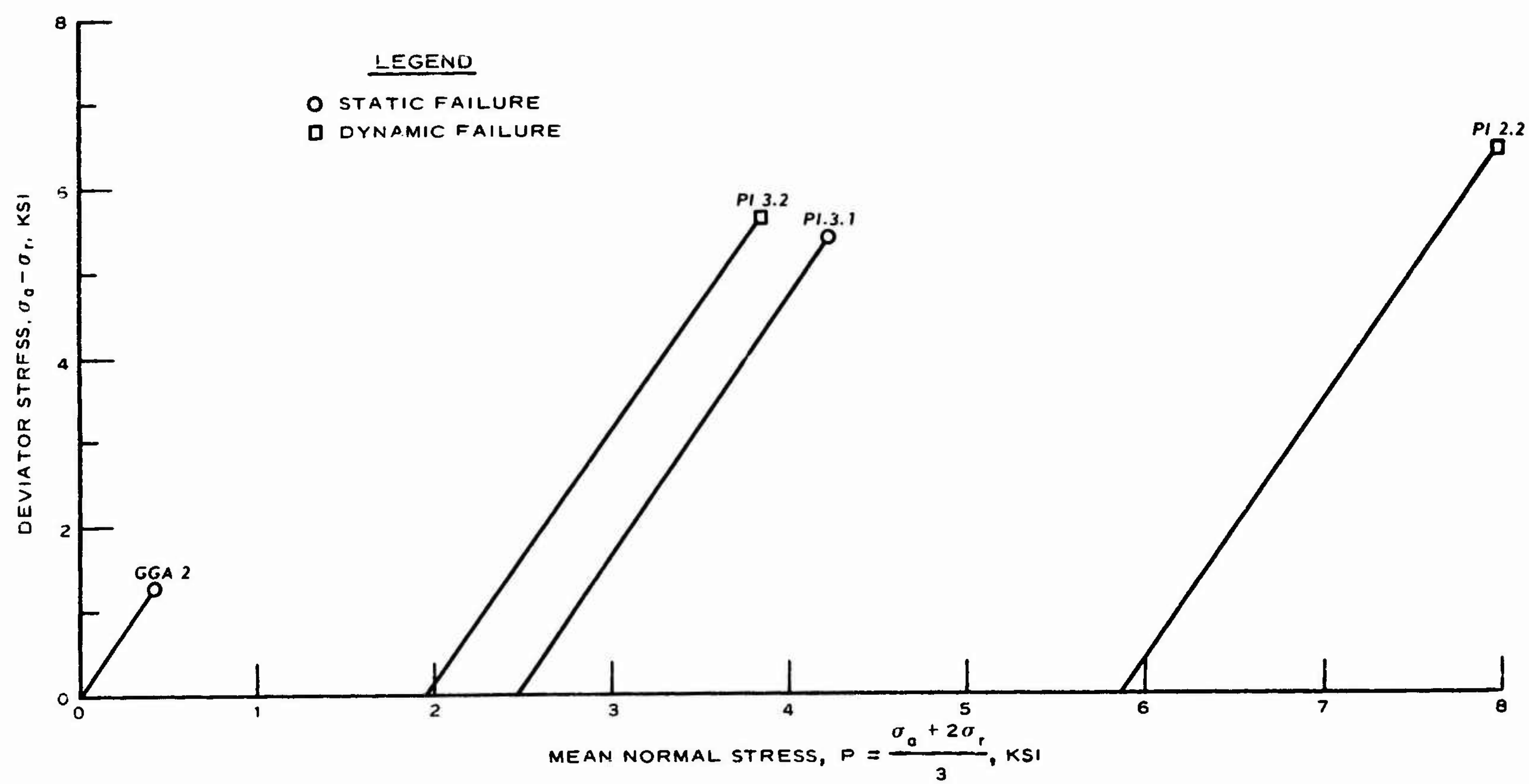


Figure 3.14 Deviator stress versus mean normal stress showing failure points for triaxial shear Tests GGA 2 and PI 2.2, 3.1, and 3.2.

CHAPTER 4

ANALYSIS AND DISCUSSION

The main purpose of this study was to determine the effect of loading rate on the stress-strain response of tuff. Although there were noticeable variations in the moisture content of the tuff specimens tested and although experimental scatter existed, some reasonable bounds can be established by which static test data can be adjusted to reflect dynamic loading conditions at the stress levels studied. These bounds to the rate effects will be examined for each test condition studied.

4.1 UNIAXIAL STRAIN TESTS

The major difference noted between the dynamic and static uniaxial strain tests was the level of stress at which the uniaxial stress-strain curve showed a softening effect (see Figure 3.4). If this phenomenon is associated with the structural collapse of the voids within the material, it appears that the material gains slight strength under dynamic loading. No rate effects were noted during the initial loading (less than 5 ksi) of the specimens. Therefore, a uniaxial stress-strain plot for a static test could be adjusted to reflect the observed dynamic response by increasing by 15 to 20 percent the stress level at which softening occurs.

It should be noted that the uniaxial strain tests were conducted on tuff with an average water content of 18 percent. Measurements indicated that a much wetter tuff exists in situ. Therefore, the in situ tuff has a lower air void content. If the in situ material is in fact nearly or completely saturated, then the above-mentioned collapse of voids may not occur. The results of these tests are probably valid only for materials that have been exposed and allowed to lose water.

4.2 HYDROSTATIC TESTS

The hydrostatic loading test results do not indicate a clear trend because of the variation in water content and the apparent data scatter. Specimens PI 4.1 and 2.1 are estimated to have lower water contents than Specimens PI 3.1, 3.2, and 2.2. The approximate secant bulk moduli to

2 ksi for the two dynamically tested specimens with the higher water contents (PI 3.2 and 2.2) vary from 1.3 ksi (PI 2.2) to 0.5 ksi (PI 3.2). The comparable statically tested specimen, PI 3.1, has an approximate secant bulk modulus of about 0.35 ksi, as shown in Figure 3.12. Although Tests PI 3.1 and 3.2 were conducted only to relatively low stress levels, the ratio between the dynamic and static bulk moduli from these two tests may provide some means by which limits to rate effects can be obtained. The ratio of dynamic to static bulk modulus based on this limited data could be as high as 1.6 and probably is not lower than 1.2.

4.3 TRIAXIAL SHEAR TESTS

Five triaxial shear tests were conducted, each at a different confining pressure. Any rate effects on Young's modulus are, therefore, possibly obscured because Young's modulus for this material could be a function of mean normal stress. The only two tests conducted at comparable mean normal stress levels were Tests PI 3.1 and 3.2. The stress-strain curves for these tests are shown in Figure 3.13. The initial moduli for the two test specimens were about equal. At higher deviator stress levels, however, the statically tested specimen (PI 3.1) had a higher modulus than the dynamically tested specimen (PI 3.2). At maximum stress, i.e. failure, the strain in the dynamically tested specimen was 14 percent greater than that in the statically tested specimen. As shown by the curves, the rate effects appear to be negligible for this one core for which close comparison is possible.

The failure strength of the tuff material appears to show a slight rate effect for an average water content of 22 percent. Two dynamic tests (PI 3.2 and 2.2) and one static test (PI 3.1) were conducted at that water content. The ratio of dynamic strength to static strength was apparently no greater than 1.1 for these tests.

CHAPTER 5

SUMMARY

The material received by WES had water contents ranging from 22 to 25 percent. Two types of static and dynamic tests were conducted on the Diamond Mine tuff; uniaxial strain tests, and triaxial tests consisting of a hydrostatic test phase and a shear phase. All of the tests were conducted on tuff that had lost some water due to the trimming techniques used.

The rate effects observed in the stress-strain and strength data were quite limited, as shown below:

1. In the series of uniaxial strain tests of specimens with water contents of about 18 percent, the stress level at which the material appeared to soften was about 15 to 20 percent greater in the dynamic tests than in the static tests. No differences were noted in the initial constrained moduli.

2. In the hydrostatic tests (water content approximately 22 percent), the dynamic bulk modulus appeared to increase over the static bulk modulus. The ratio of dynamic to static bulk modulus could only be roughly determined within the available data. It may be as low as 1.2 or as high as 1.6.

3. In the shear tests, the strain at failure was slightly greater for the dynamic tests than for the static tests, and the dynamic strength may be 10 percent greater than the static strength.

In general, the strain rate dependence of the tuff appears to be of only secondary importance in the development of constitutive relations for this material. It is recommended that primary consideration be given to the development of constitutive relations derived from test data on the tuff at its in situ water content because the data indicate that the gross features of the response of the material are controlled by the amount of water it contains.